EVALUATING BED-MATERIAL TRANSPORT EQUATIONS USING FIELD MEASUREMENTS IN A SANDY GRAVEL-BED STREAM, ARBÚCIES RIVER, NE SPAIN

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ABSTRACT

Bed-material load under a wide range of hydraulic conditions was sampled in a poorly sorted, sandy, gravel-bed river (Arbúcies, NE Spain) during 1991 and 1992. The Arbúcies data showed a marked scatter of bed-material discharges, reflecting the high variability of bedload rates as well as of suspended sediment concentrations. Bed-material discharges were used to test five bedload and bed-material formulae. The degree of agreement between observed and predicted values varies greatly. The percentage of observations in which the discrepancy ratio between observed and computed values has a value between 0·5 and 2, range from 25 per cent (van Rijn), to 38 per cent (Brownlie), 52 per cent (Meyer-Peter and Müller), 65 per cent (Engelund and Hansen), and 68 per cent (Ackers and White). The wide range of hydraulic conditions from which the data were obtained and the poor sorting of the bed sediment affected the performance of the van Rijn (1984) and Brownlie (1981) equations. The degree of correlation between observed transport rates and values predicted by the Engelund and Hansen (1967) formula appears to be unaffected by the poorly sorted bed material of the Arbúcies River. The Meyer-Peter and Müller (1984) model predicted bedload transport in the Arbúcies River with reasonable accuracy and no bias for transport values under low and intermediate flow conditions. The best agreement with measured values was obtained using the Ackers and White (1973) model, a reflection of its original design for poorly sorted sediment. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

Sediment load in an alluvial channel is the result of the movement of individual particles, which are transported by rolling, saltation, or in suspension by streamflow. Bed-material load is defined as the amount of sediment originating from the streambed, passing through a given cross section, as either bedload, suspended load, or both. Stream discharge is the primary factor controlling the transport of bed material, which moves episodically through the channel (Church *et al*., 1987). Many attempts have been made to determine bedload discharge (e.g. Lane and Borland, 1951; de Vries, 1973; Leopold and Emmett, 1976; Reid *et al*., 1980; Ergenzinger and Custer, 1983; Carey, 1985; Diplas, 1987) and bed-material load (e.g. Colby and Hembree, 1955; McPherson, 1971; Andrews, 1981). However, simultaneous measurements of both components of the bed-material load are still not commonly available, even for steady low flows.

One of the main problems in measuring bed-material transport is that, under natural conditions, bedload discharge is not a steady process and variations up to more than 50 per cent may be expected (e.g. Dietrich and Gallinati, 1991). Numerous sampling devices and field techniques have been developed to measure bedload and suspended load. No sampler, however, can cope adequately with the wide range of hydraulic and sediment discharge conditions founded in natural streams (Hubbell *et al*., 1981). Problems related to the calibration of the

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sampling apparatus have been widely described (e.g. Emmett, 1979), mostly related to the effects on sampling accuracy of variations in bed-material discharge, due to the movements of bedforms in sand-bed rivers (Gomez *et al*., 1989) and gravel-bed rivers (Lekach and Schick, 1983; Hassan and Reid, 1990). Owing to the extreme temporal variability of transport rates, bedload sampler calibrations derived from averages of groups of samplers and measured rates are subject to error, unless the sampler has a constant sampling efficiency for all instantaneous transport rates (Hubbell, 1987).

Because of difficulties in field measurements of bedload discharge, a large number of transport formulae have been developed for a wide range of sediment sizes and hydraulic conditions. These formulae are based on the premise that specific relations exist between hydraulic variables, sedimentological conditions, and rates of bedload transport. However, most bedload transport theoretical models have been derived from flume experimental data (e.g. Hamamori, 1962) under uniform steady flow conditions, rather than from natural flow and transport observations (Gomez and Church, 1989). For example, less than 70 per cent of predicted sediment transport rates of the best performing equations evaluated by White *et al*. (1975) lay between one-half and twice the observed values. In addition, bed-material formulae assume similarity in sediment transport and are restricted-equilibrium formulae, although it is not certain that river channels act in that way.

Andrews (1981) showed that the best equations predicting bed-material discharges, within a range of one-half to twice the observed values, lay between 60 and 79 per cent of the observations. Little is known, however, about the performance of these equations in sandy gravel-bed rivers. Accordingly, there remains a need for more comparisons between measured bedload and bed-material transport and computed values from bedload and bed-material transport formulae. The main aim of this paper is to compare bed-material transport rates in the sandy gravel bed of the Arbúcies River, based on field measurements of bedload and suspended load under different hydraulic conditions, with predicted values from several bed-material and bedload transport formulae.

STUDY SITE

The study site is located in the Arbúcies River, one of the main tributaries of the Tordera River, Catalan Coastal Ranges (NE Spain). At the study reach the drainage area is 106 km^2, about half of which drains the northeastern part of the plutonic massif of Montseny. More than 95 per cent of the drainage basin is covered by granitic rocks, biotitic medium-grain granodiorite being most common. Quaternary deposits consist of three Holocene terrace levels, with sand and fine gravels predominant. Mean annual precipitation is 984 mm with a coefficient of variation of 30 per cent. The hydrological regime is characterized by a high seasonal variability; wet months occur during spring, late autumn, and early winter, with a mean monthly precipitation higher than 100 mm. The 25-year record of flows, 1967–1992, shows that streamflow is continuous except for 2 per cent of the time (Batalla and Sala, 1995). Mean flow is 1·07 m^3 s^{-1} and the streamflow variability index (Lane and Lei, 1950) is 0·39. Floods attain 65 m^3 s^{-1} (with an estimated recurrence interval of 50 years, calculated from the Gumbel (1958) distribution). The flash flood magnitude index (Baker, 1977) is 0·52.

Figure 1 illustrates the rainfall and the streamflow recorded in the catchment area of the Arbúcies River between October 1991 and December 1992. During the study period several flood events occurred. The largest started on 1 December 1991, with 205 mm of rainfall in 72 hours, and yielded a peak discharge of 13 m^3 s^{-1} (with an estimated recurrence period of 2·5 years). In addition, several medium floods with peak discharges close to or slightly higher than the bankfull stage (4 m^3 s^{-1}, equalled or exceeded 2·2 per cent of the time) occurred in December 1991, and January, June and December 1992.

The bulk samples of the bed material were taken from a bar located upstream of the measuring section. The size of the samples was determined according to Church *et al*. (1987). Grain-size distribution of the river-bed material is shown in Figure 2. The median size of the sediment is 2·2 mm and d_{95} is 71 mm. The river-bed material is mainly poorly sorted sandy gravell, with a sorting coefficient of 7, calculated from the equation:

$$\sigma_g = 0{\cdot}5\,[(d_{84}/d_{50}) + (d_{50}/d_{16})]$$

where σ_g is bed-material sorting, and d_{16}, d_{50}, d_{84} are the respective percentile fractions of the bed-material size distribution in millimetres. The median size of the sediment of the river banks is 0·7 mm. Bed slope at the study site is 0·0095.

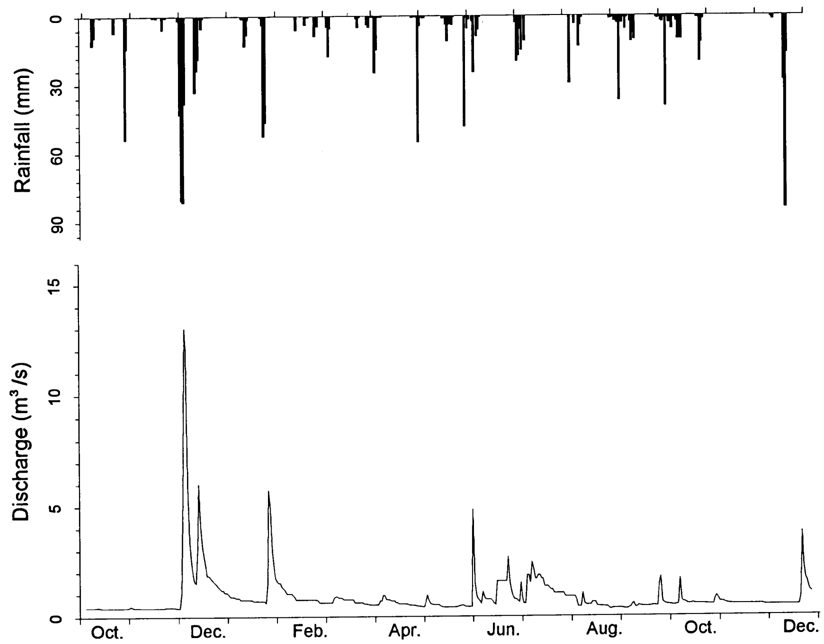

Figure 1. Rainfall and runoff in the Arbúcies catchment area during the study period (October 1991–December 1992)

DATA COLLECTION

Weekly flow measurements and samples of suspended load and bedload were obtained at the outlet section of the Arbúcies River, upstream of its confluence with the Tordera River. In addition, several samples were taken during small and medium flood events during the study period (1991–1992). The samples cover a wide range of hydraulic conditions and almost 98 per cent of the total range of discharges, as well as sediment transport rates (Figure 3). The mean flow velocity was measured at 0·6 m depth from the water surface, at 0·5 m intervals across the channel width. The samples were taken at low flows when the streambed had formed into dunes. No information is available on bedforms during high flows.

A Helley-Smith sampler with a 76·2 mm intake, 0·45 mm mesh and 15 kg capacity was used to sample the bedload discharge. Seventy integrated bedload samples were collected every 1 m across the channel section. The sampling time ranged between 5 and 10 minutes. As reported by Emmett (1979), for particle sizes greater than 0·5 mm and smaller than 16 mm, the trap efficiency of the sampler reached 100 per cent, irrespective of the changes in transport rates, while in the case of particles larger than 16 mm efficiency dropped to less than 70 per cent. Bedload samples obtained in the Arbúcies River appear to support this statement, since no particle larger than 55 mm (d_{92} of the bed-material distribution) was ever collected.

Two-hundred-and-thirty vertically integrated suspended sediment samples were taken using a U.S. DH48 hand-held sampler. Two samples of 0·5 litres were obtained during each sampling performance. The sampler was lowered to approximately 10 cm above the streambed surface, taking care to avoid contact. Suspended-sediment concentration was determined after filtering the sample with 0·45 μm mixed cellulose esters. Unit rate of suspended sediment transport was obtained by multiplying the obtained concentration by the discharge, and dividing the result by the width of the streambed.

Because washload is not included in the bed-material load, the concentration of washload in the stream at a given time or discharge depends upon the immediate supply of washload sediment to the channel rather than on hydraulic conditions (Andrews, 1981). In the case of the Arbúcies River, the streambed acts as the most active sediment source of the catchment area (16 tonnes ha^{-1} a^{-1} against 0·75 tonnes ha^{-1} a^{-1} from the hillslopes); the washload contribution is often negligible, especially at low and medium flows below the bankfull discharge. This study considers only the bed-material discharge.

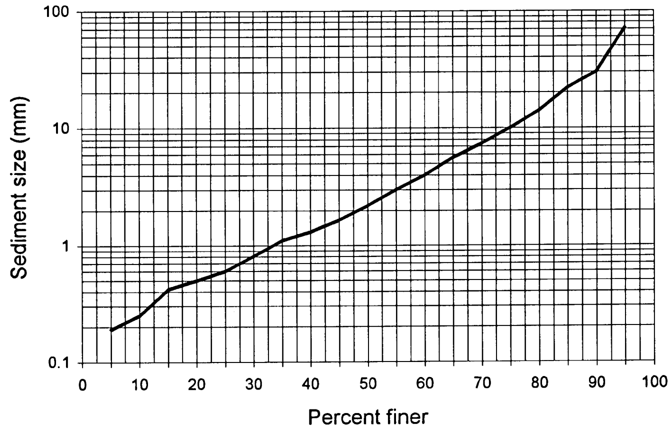

Figure 2. Bed-material size distribution of the Arbúcies River

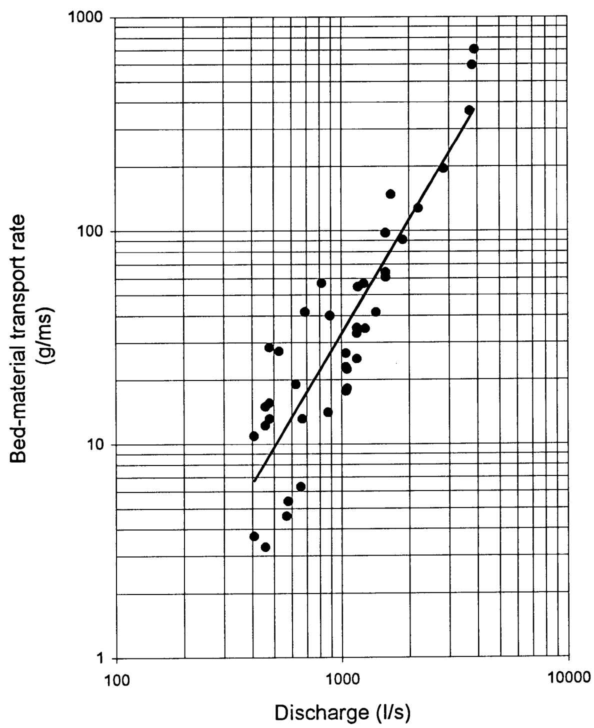

Figure 3. Rating curve between discharge and bed-material transport in the Arbúcies River, computed from the bedload transport and the suspended-sediment concentrations

COMPUTATION OF THE BED-MATERIAL LOAD

The mean bedload transport rate (i_b) is 38 g m^{-1} s^{-1} (submerged weight), ranging from 1 g m^{-1} s^{-1} at low discharges to 280 g m^{-1} s^{-1} during bankfull discharges (Batalla and Sala, 1995). Bedload transport variability during floods close to bankfull discharge, at 10 min sampling intervals, varies between 80 and 100 per cent during most floods; it reached 600 per cent (from 10 to 64 g m^{-1} s^{-1}), the largest measured short-term variability, during the flood event of 1 June 1992. Bedload transport in the Arbúcies River is closely related to the continuous movement of the sediment on the channel bed. Field observations indicate that only 8 cm of water depth (0·210 m^3 s^{-1}) is needed to entrain the sand. This flow depth is equalled or exceeded 80 per cent of the time. The mean bed shear stress associated with an 8 cm depth is 9 N m^{-2}, four times larger than that calculated

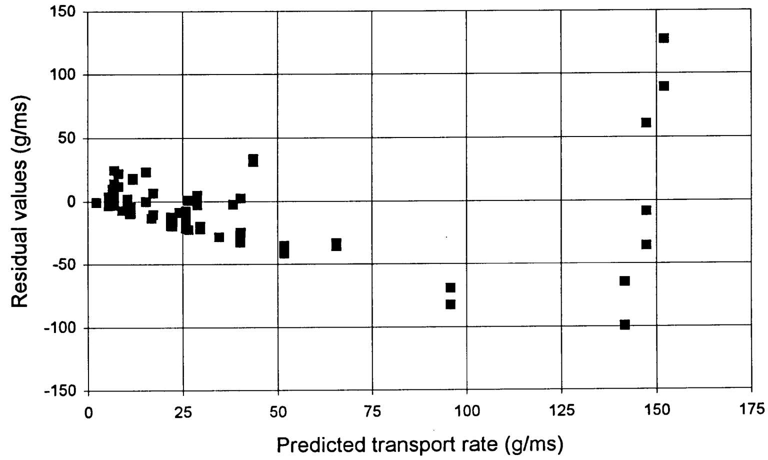

Figure 4. Residuals analysis for the bedload transport data in the Arbúcies River. Poor fit is indicated by curvature

using the classical entrainment function of Shields (1936). The presence of bedforms can significantly increase the shear stress necessary to entrain particles if compared with critical values for flat beds (Andrews, 1983). In addition, bed-material size distribution can also affect the forces acting on a given particle in the river bed.

The relation between bedload and discharge, although statistically significant, shows a low degree of statistical correlation ($r^2 = 0{\cdot}47$ (Batalla and Sala, 1995)). Residual analysis of the relation between bedload transport rates and discharge (Figure 4) indicates a non-linear trend between both variables. The analysis shows two distinct trends in terms of the relation between predicted and observed bedload transport rates, with a cutoff at predicted rates of about 140 g m^{-1} s^{-1}. Bedload transport rates above this value are generally obtained during discharges close to or at bankfull stage. Furthermore, the figure shows a high scatter of points above the same value. Altogether, the figure illustrates the high variability of bedload transport in this river, this phenomenon being especially intense at bankfull discharges. This is thought to be linked to the destruction of the surface armoured layer and the release of large amounts of material ready to be transported (Batalla and Sala, 1995). Moreover, residual analysis indicates difficulties in predicting bedload transport at bankfull discharges using the statistical relation between bedload and discharge obtained from data below that stage. In order to improve the adjustment between bedload rates and discharge, a simple log transformation of the parameters was performed. The statistical bias during the back-transformed procedure was removed by applying the correction factor developed by Ferguson (1986).

Mean suspended sediment concentration is 191 mg l^{-1} with a coefficient of variation of 154 per cent. Concentration varies from 1 mg l^{-1} during low flows to 2670 mg l^{-1} during flood events. The relation between suspended-sediment concentration and discharge showed a higher degree of statistical correlation ($r^2 = 0{\cdot}75$ (Batalla and Sala, 1994)). The scatter of points observed in the Arbúcies River between suspended-sediment concentration and discharge is a very typical situation in sediment transport systems (Knighton, 1984). The statistical bias of this relation during the back-transformed procedure was also removed by applying the factor developed by Ferguson (1986). The corrected rates of suspended-sediment transport were added to the measured bedload transport rates in order to obtain the total bed-material discharge (Table I). Figure 3 illustrates the statistical relation between bed-material load (i_b in g m^{-1} s^{-1} of submerged weight) and water discharge (Q in l s^{-1}), as defined by the equation (statistically significant, p,<0·01):

$$i_b = 0{\cdot}00015\, Q^{1{\cdot}78} \; (r^2 = 0{\cdot}80; n = 40)$$

Similar statistical relations have been reported elsewhere (e.g. Henderson, 1966). Figure 3 shows that the data are considerably scattered with a general trend of increment in the transport rates with discharge. The variability of the bed-material load is directly derived from the temporal variations of its two components: (a) bedload variability can be associated with variations of sand transport (Gomez *et al.*, 1989), changes in hydraulic conditions, or the development and migration of bedforms, especially during floods; and (b) scatter of the suspended-sediment concentrations is related either to seasonal causes or to hysteretic phenomena during floods (Batalla and Sala, 1994).

Table I. Bed-material transport data and corresponding hydraulic variables for the Arbúcies River (1991–1992). Sediment transport rates are given in submerged weight

Flow discharge ($l s^{-1}$)	Flow depth (m)	Flow velocity ($m s^{-1}$)	Bedload transport ($g m^{-1} s^{-1}$)	Suspended load transport ($g m^{-1} s^{-1}$)	Bed-material transport ($g m^{-1-1}$)	Total load conc. ($g m^{-3}$)
580	0·19	0·55	2	3	5	43
3900	0·48	0·77	349	354	703	1262
3820	0·47	0·77	260	335	595	1090
2200	0·34	0·67	37	90	127	346
1170	0·22	0·59	13	20	33	141
1580	0·27	0·63	53	45	98	308
1170	0·22	0·59	15	20	35	150
1580	0·27	0·63	19	45	64	202
1200	0·22	0·59	5	20	25	107
1060	0·21	0·56	3	15	18	86
1050	0·26	0·70	12	15	27	127
1050	0·26	0·70	3	15	18	84
1430	0·33	0·72	8	34	41	145
1050	0·26	0·70	8	15	23	110
870	0·22	0·69	4	10	14	72
660	0·20	0·60	2	5	6	43
570	0·18	0·58	1	3	5	36
1060	0·26	0·71	7	15	22	106
670	0·21	0·58	8	5	13	88
1880	0·39	0·74	21	70	91	242
1280	0·31	0·69	9	26	35	135
1190	0·32	0·62	34	21	55	230
690	0·34	0·37	36	5	42	272
1670	0·51	0·50	96	52	148	443
1260	0·46	0·46	32	24	57	224
820	0·20	0·82	48	9	57	311
480	0·31	0·31	11	2	13	109
410	0·25	0·41	9	2	11	106
460	0·31	0·30	13	2	15	129
530	0·29	0·41	25	3	27	231
410	0·23	0·45	2	2	4	36
460	0·20	0·58	10	2	12	106
890	0·35	0·57	29	11	40	202
630	0·31	0·51	15	4	19	136
480	0·30	0·40	26	2	28	237
460	0·22	0·52	1	2	3	29
480	0·26	0·46	13	2	16	129
3720	0·47	0·95	53	312	365	687
1580	0·36	0·80	16	44	61	191
2850	0·62*	0·66	16	179	195	411

* Due to technical difficulties, discharge was measured upstream from the monitored section

COMPARISON BETWEEN MEASURED AND COMPUTED BED-MATERIAL DISCHARGES

Several studies have examined the degree of correlation between bedload and bed-material discharge equations and measured values either in a flume or in the field (e.g. White *et al.*, 1975; Andrews, 1981). They expressed the discrepancy between the observed transport rates and the predicted transport rates as the ratio between i_b predicted and i_b observed, where i_b is either the bed-material or the bedload discharge. White *et al.* (1975) tested eight of the more extensively used bed-material discharge equations. Only three of these equations (Rottner (1959), Engelund and Hansen (1967) and Ackers and White (1973)) had discrepancy ratios between 0·5 and 2·0 more than 50 per cent of the time. Andrews (1981) examined the bedload transport equations developed by Engelund and Hansen (1967), Yang (1973), Shen and Hung (1972) and Ackers and White (1973). The

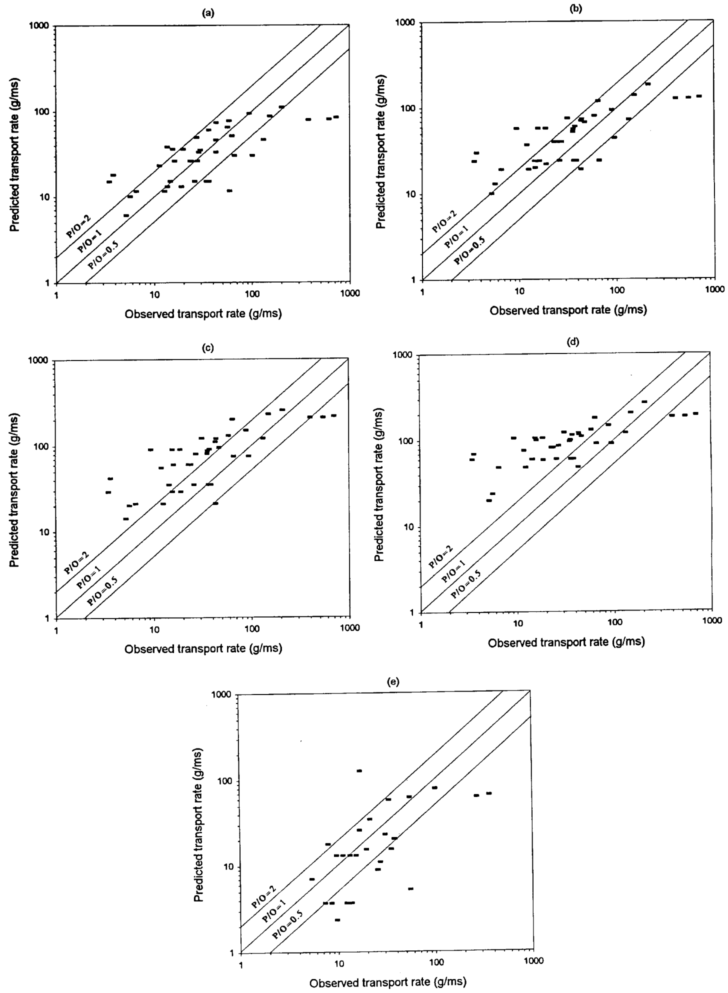

Figure 5. Comparison of bed-material discharges measured in the Arbúcies River with the predicted bed-material discharges using the following formulae: (a) Ackers and White (1973); (b) Engelund and Hansen (1967); (c) Brownlie (1981); (d) van Rijn (1984); (e) Meyer-Peter and Müller (1948)

percentage of observations in which the discrepancy ratio lay between 0·5 and 2·0 were: Engelund and Hansen; 79 per cent, Yang, 60 per cent; Shen-Hung, 71 per cent, and Ackers and White, 66 per cent. Gomez and Church (1989) tested 12 bedload sediment transport equations developed for use in gravel-bed rivers. They concluded that none of these formulae was capable of generally predicting bedload transport in gravel rivers. Despite this, the authors pointed out that for evaluating the magnitude of bedload transport on the basis of limited hydraulic information, stream power equations should be used.

In this study, Arbúcies River data were compared with four widely used bed-material discharge equations (Engelund and Hansen (1967), Ackers and White (1973), Brownlie (1981) and van Rijn (1984a,b)), and one bedload discharge formula developed by Meyer-Peter and Müller (1948).

The Engelund and Hansen equation was designed to predict sediment transport when the streambed is formed into dunes; it applies to median-sized sand or coarse sediments, but it excludes poorly sorted sediment. The Ackers and White function is a tractive force formula, developed for non-uniform sediment (0·04–4·94 mm) by combining three dimensionless parameter groups (particle size, mobility and transport rates). It is applicable to hydraulic conditions where the streambed is formed into ripples, dunes or plane bed (Andrews, 1981). The Brownlie equation is a dimensional bed-material transport model developed only for sand, with d_{50} between 0·063 and 2·0 mm, and for sorting coefficient (σj_g) less than 5. Van Rijn (1984a,b) developed two-dimensional bedload transport formulae which enable the computation of both suspended-sediment transport and bedload transport as the product of saltation

height, particle velocity, and bedload concentration. The function was tested for particle sizes between 0·2 and 2·0 mm. The Meyer-Peter and Müller formula is among the best-known tractive force formulae. It is a modification of the Meyer-Peter *et al.* (1934) formula, which was derived from a considerable number of experiments with uniform, graded and light-weight material (Gomez and Church, 1989). It is recommended for use with 0·4 to 28·6 mm uniform sediment or mixtures, also in steep rivers, and with high rates of bedload transport.

Figure 5 illustrates the comparison between the observed and the computed values. The percentage of observations in which the discrepancy ratio between observed and predicted bed-material transport had a value between 0·5 and 2 were: Ackers and White, 68 per cent, Engelund and Hansen, 65 per cent, Brownlie, 38 per cent, and van Rijn, 25 per cent. Fifty-two per cent of the observed and predicted values according to Meyer-Peter and Müller had a discrepancy ratio between 0·5 and 2. The Meyer-Peter and Müller (1948) threshold value is 20 cm of water depth which is 2·5 times that observed in the field for the initiation of motion.

The degree of concordance between measured values in the field and computed data according to the Ackers and White (1973) and Engelund and Hansen (1967) equations is similar to that obtained by White *et al*. (1975) and Andrews (1981). The discrepancies between measured and predicted values are similar when Arbúcies River data are compared with the flume measurements from which these formulae were derived. The performance of the Engelund and Hansen (1967) model appears to be unaffected by the poorly sorted bed material of the Arbúcies River. The Engelund and Hansen (1967) equation was developed for bedforms in alluvial channels. Apparently, this has more influence on the performance of the equation than does sediment-size sorting. For the range of sediment transport 10–100 g m^{-1} s^{-1}, the Ackers and White and Engelund and Hansen equations showed an excellent agreement with the observed values. Eighty-six per cent of observations had discrepancy ratio between 0·5 and 2. However, they are inapplicable to the transport phase associated with bankfull or close to bankfull discharges in the Arbúcies River.

The Brownlie (1981) and van Rijn (1984a,b) functions performed poorly. These functions tended to predict higher values of bed-material transport than those measured in the Arbúcies River: the lower the bed-material transport rate, the poorer the correlation between predicted and measured transport rates. This can be explained by the lack of adjustment between the Arbúcies grain-size distribution and some of the conditions from which these formulae were derived. The Brownlie (1981) equation was developed for: (a) sandy material with a d_{50} smaller than 2 mm; (b) a sorting coefficient (σ_g) lower than 5; and (c) a ratio of water depth and median sediment size lower than 100. The first two limitations of the function are not met by the bed material of the Arbúcies River, although they do not differ greatly from the original conditions for applying the equation. Moreover, the use of the Brownlie formulae in the Arbúcies River is restricted to a water depth below 0·2 m, since the relation between depth and median sediment size is higher than 100. Despite these constraints, the Brownlie (1981) formula may be used in the Arbúcies River to predict bed-material discharges during high flows, having a 65 per cent agreement between measured and computed values of bed-material transport above 100 g m^{-1} s^{-1}. The limiting condition of the van Rijn (1984) formula for the calculation of the suspension number, $0{\cdot}01<\omega/u_*<1{\cdot}00$, (where ω is the particle settling velocity (m s^{-1}) and u_* the shear velocity (m s^{-1})) is also not fulfilled by the Arbúcies data below 0·23 m of water depth. Discrepancy, however, is small.

Of the values predicted by the Meyer-Peter and Müller (1948) equation for bedload between 10 and 100 g m^{-1} s^{-1}, 66 per cent have a discrepancy ratio between 0·5 and 2 times the field data. Predicted values during floods are lower than those observed in the field.

DISCUSSION AND CONCLUSIONS

Bedload transport rates obtained in the Arbúcies River are of similar magnitude to those reported for the East Fork River in Wyoming (Leopold and Emmett, 1976). Arbúcies data are very scattered, hypothetically due to the variations of transport rates associated with the migration of bedforms during sampling, especially at flows close to bankfull discharges. As pointed out in the literature (e.g. Gomez *et al*., 1989), short-term temporal variations in bedload transport rates associated with the passage of bedforms are an inherent component of the bedload transport processes. The identification of such variations is controlled by the duration and frequency of sampling and the length of sampling time, with respect to the period of bedform(s) in question. In the case of the Arbúcies River, sampling time was, on occasions, presumably less than that required to identify the movement

of the bedforms in the channel. This could partly affect the accuracy of the results.

The application of bed-material and bedload discharge equations is limited to the range of hydraulic conditions and sediment characteristics for which the functions were formulated (Andrews, 1981). The wide range of hydraulic conditions from which the data were obtained in the Arbúcies River and the poor sorting of the bed sediment affected the performance of the van Rijn (1984) and Brownlie (1981) equations. This did not apparently influenced the degree of correlation of the values predicted by the Engelund and Hansen (1967) formula. The Meyer-Peter and Müller (1948) formula predicted bedload transport in the Arbúcies River with reasonable accuracy and no bias, especially for those values of transport under low and intermediate flow conditions. The Ackers and White model shows the best agreement with the measured values, reflecting its original design for poorly sorted sediment (Ackers and White, 1973), although the degree of concordance drops and the bias increases significantly during low flows, with transport rates under $10\,g\,m^{-1}\,s^{-1}$. This may be due to the influence of gravels on the delay of entrainment of sand particles.

It has been suggested (e.g. Andrews, 1981; Gomez and Church, 1989) that bed-material or bedload discharge equations, giving a reasonable estimation of the actual discharge, are preferable to field measurements because of the uncertainty, expense and time-consuming processes involved in the latter. The data base on sediment flux obtained in the sandy gravel streambed of the Arbúcies River has shown that some formulae are reasonably capable of predicting bed-material transport; the percentage of observations in which the discrepancy ratio between observed and computed values has a value between one-half and two times the field data reached 65 per cent for some of the tested equations. However, most of the available models consider sediment transport as a steady one-dimensional process, since they were developed from flume experimental data under hydraulically uniform conditions. It is clear that temporal and spatial variability should be regarded as an inherent characteristic of the bedload transport processes and that equilibrium transport is rarely attained under natural streams. Therefore, it is important to increase efforts to explain variations of bedload transport in the light of the major interactive processes controlling sediment supply, specifically channel morphology (including particle size) and hydraulic conditions of flow. More field data on sediment transport under different and changing hydraulic conditions are thus required to achieve a better assessment of bed-material fluxes in channel beds; eventually, this would lead, for example, to a more reliable estimation of sediment yield of drainage basins. In order to gather high temporal and spatial resolution data on sediment transport, available prototypes for continuous monitoring of processes of bed-material transfer in gravel-bed rivers (e.g. pressure pillows) need to be further developed and modified in order to broaden their applicability; this need is even more important in the case of sand and sandy gravel-bed streams, where the full spectrum of sediment transport modes occurs under almost all hydraulic conditions, and especially during flood events.

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